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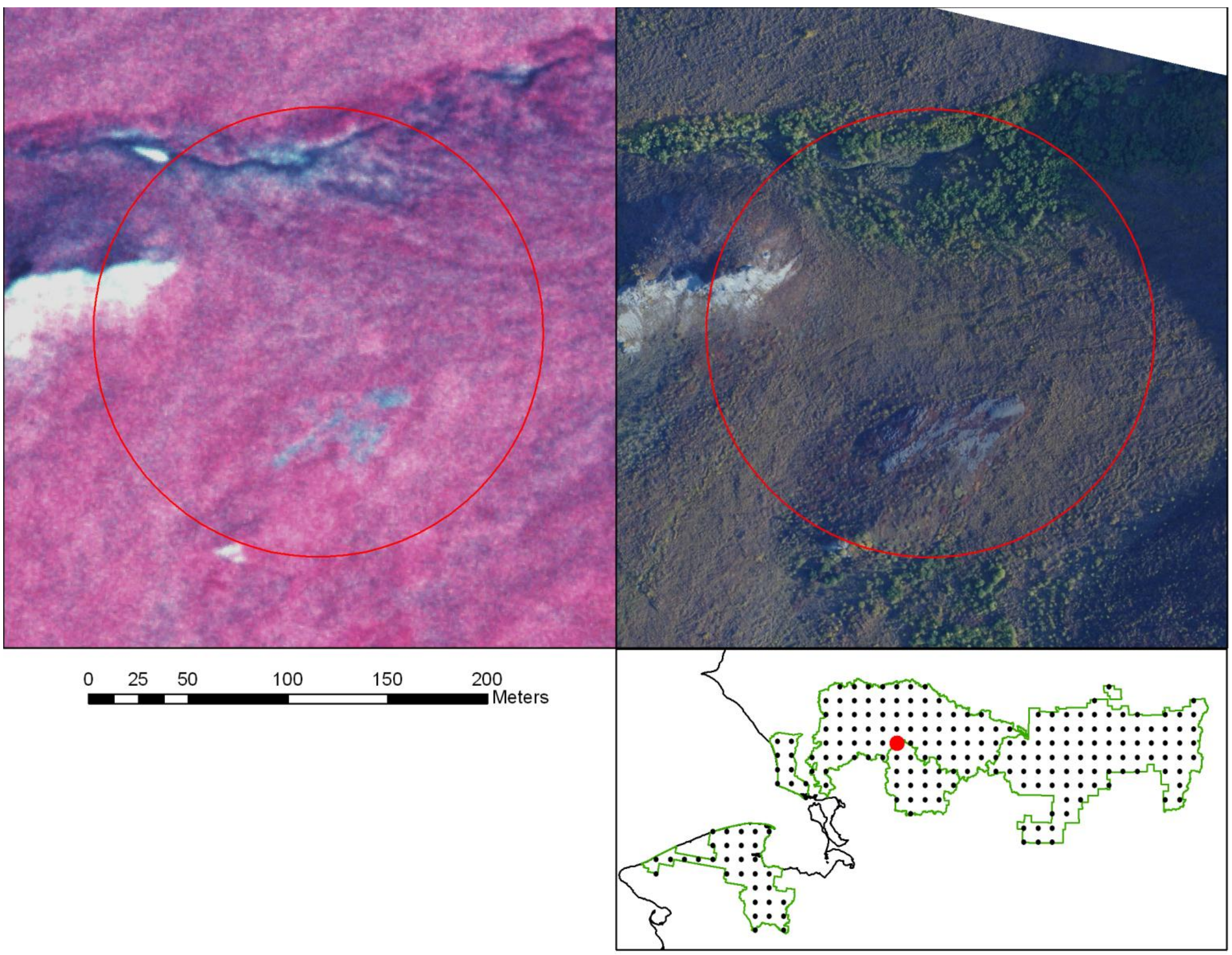
Natural Resource Stewardship and Science

Three Decades of Landscape Change in Alaska's Arctic National Parks

Analysis of aerial photographs c. 1980-2010

Natural Resource Technical Report NPS/ARCN/NRTR—2013/668



ON THE COVER

Tall shrub increase on tundra. An area of mostly herbaceous and low shrub vegetation in 1979 (AHAP color-infrared photo, left) was colonized by tall shrubs by 2008 (small-format true color photo, right). The grayish area along the creek on the 1979 photo is probably a snow bed, note the small residual patch of snow (on 12 July) along the creek just outside of the plot to the left. The red dot on the inset map shows the location of the plot in the Noatak National Preserve, Alaska (Plot NOAT_-25_200.)

Three Decades of Landscape Change in Alaska's Arctic National Parks

Analysis of aerial photographs c. 1980-2010

Natural Resource Technical Report NPS/ARCN/NRTR—2013/668

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Abstract

Changes in vegetation, water bodies, and landforms in the NPS Arctic Inventory and Monitoring Network (ARCN) over the past approximately 30 years were documented by comparing recent (2008-2010) and c. 1980 aerial photography. High-resolution color digital aerial photographs were taken on a systematic grid of 206 plots with 20-km spacing across the five National Parks of ARCN in 2008-2010. These photographs were georeferenced and compared to scanned and georeferenced color-infrared aerial photographs from the Alaska High-Altitude Project (AHAP), which have complete coverage of ARCN between 1977 and 1985. Two types of data were collected from the photographs: 1) visual evaluation of change between the two dates within a 4-ha circular plot for tree cover, shrub cover, barren area, lichen cover, wetland area, surface water area, and ice-wedge polygons. Cover changes were classified as "increase", "no change", or "decrease" between the two dates, and the mechanism of change was also classified. For example, shrub increases were classified as "increase on tundra", "post-fire succession", "floodplain succession", "increase on wetland", or "other primary succession". Changes in the form of ice wedge polygons for the 4-ha plot as a whole were also recorded. Ice wedge polygons are a permafrost landform that can become more high-centered due to permafrost thaw. 2) Classification of the ecotype (vegetation/land cover type) for each of 37 hexagonal subplots within the 4-ha circular plot for both photo dates, using the classification scheme from ARCN's ecotype map (Jorgenson et al. 2009). Ice-wedge polygon morphology in the hexagonal subplots was also classified for both photo dates. Tallies of these subplot classes provided an estimate of the area covered by ecotypes and ice wedge polygons on the two image dates.

The majority of the 206 plots (76%) showed no change detectable by comparison of the photo dates in any of the features. Changes of all kinds were disproportionately concentrated in the lowlands, especially in areas below 305 m (1000 feet) elevation. The most common changes were shrub increase on tundra (15 plots), shrub increase due to floodplain succession (5 plots), tree increase due to post-fire succession (10 plots), tree increase due to colonization of tundra (4), and surface water increase due to thermokarst (6 plots; thermokarst is land surface subsidence due to thaw of permafrost). Changes in barren areas and lichen-dominated areas were minimal. Ice wedge polygons showed minor degradation on 2 of the 21 plots with wedges present.

Changes in the estimated area of various ecotypes on the plots mirrored these plot-level change categories. The preponderance of area (94%) had no ecotype change registered. The most common ecotype changes were increases in forest and tall shrub types on undisturbed tundra and in previously forested areas as a result of post-fire succession, and changes between riverine barrens and various riverine vegetation types due to channel migration and succession. About a third of the sample area in "Lowland black spruce forest" on the c. 2010 photos had developed by succession since c. 1980. As a result of shrub increase on tundra, an estimated 14% of the area in the ecotype "Upland alder willow tall shrub" on the c. 2010 photos was new since c. 1980.

Our sample of 206 systematic photos plots is probably not large enough to quantify certain landscape changes specific to lowland areas, which cover only about one quarter of ARCN. Thus ARCN is planning more intensive monitoring techniques targeted to specific features such as water bodies and thermokarst landforms.

Acknowledgments

Thanks to M. Torre Jorgenson of Alaska Ecoscience for the original idea of a 20-km grid of small-format aerial photographs as a monitoring tool in ARCN. Thanks to Tom George of Terra-Terpret photography and Matt Nolan of the University of Alaska Fairbanks for high-resolution aerial photography. Jay Ver Hoef provided statistical advice, R programming help, and wrote the "Probability Testing" paragraph of the Methods. Janet Jorgenson of the US Fish and Wildlife Service, and Amy Miller, Jim Lawler, and Scott Miller of the National Park Service provided helpful review comments.

Introduction

Arctic landscapes are constantly changing. Certain plants may locally become more abundant, colonize new areas, or die out; permafrost forms and thaws; wildfires burn and then vegetation grows back; rivers erode, meander, and deposit new sediment; ponds and lakes form and then dry up or drain; and slope processes change the land shape. These processes have occurred for millennia, presumably in some kind of dynamic near-equilibrium across the landscape. But in recent decades some changes appear to have become dominant, potentially representing large-scale shifts in the landscape from one state to another (Hinzman et al 2005). However, the rates, location, and prevalence of many of these environmental changes have yet to be quantified.

Probably the most well known landscape change in the Alaskan arctic is the increase in shrubs that has occurred in the arctic since the first aerial photographs were taken in the 1950s, apparently as a result of climatic warming (Tape et al. 2006; Myers-Smith et al. 2011). Shrubs can also increase on tundra as a result of wildfires (Racine 2010). Shrubs favor browsing species (e.g. moose, as well as ptarmigan, Tape et al. 2010). They also could reduce erosion by vegetating bare areas along streams (Tape et al. 2010), lead to greater fire frequency by increasing fuels (Higuera et al 2009), and accelerate warming by decreasing albedo (Chapin et al. 2005). Climate warming has also led to a minor increase of trees in ARCN (Suarez et al. 1999, Sullivan and Sveinbjörnsson 2010).

Lichens are of particular interest in the arctic as a major source of biodiversity and caribou forage (Holt and Neitlich 2010). The future could bring a decrease in lichen diversity and abundance as a result of herbivory, increases in fires, and increased competition with other plants such as shrubs (Joly et al. 2009, Land et al. 2012).

Thaw of permafrost, as manifested in thermokarst and melting of massive ice wedges, has also been observed in arctic Alaska (Jorgenson et al. 2006). Thaw of permafrost, along with climate-driven changes in the water balance, have also been implicated in the decrease in area of lakes and ponds in northern Alaska over the past 50 years (Yoshikawa and Hinzman 2003, Riordan et al. 2006).

The terrestrial landscape patterns and dynamics vital sign of the NPS Arctic Inventory and Monitoring Network (ARCN; Fig. 1) is concerned with documenting and understanding these widespread ecological changes in the northern Alaskan National Parks. As a part of this monitoring program, we are using repeat photography to track changes in vegetation, water bodies, and certain landforms. The present study compares recent (2008-2010) high-resolution aerial photographs with our best complete set of historical aerial photographs to document changes that have occurred in ARCN over the past 30 years. Our plan is to repeat these high-resolution aerial photographs at 10- to 20-year intervals in the future and repeat the analysis made here, in order to detect future changes.

Study Area

Change analysis was based on comparison of two image dates at sample points on a systematic grid that covers all of ARCN (Fig. 1). These grid points have 20 km spacing from a random starting point.

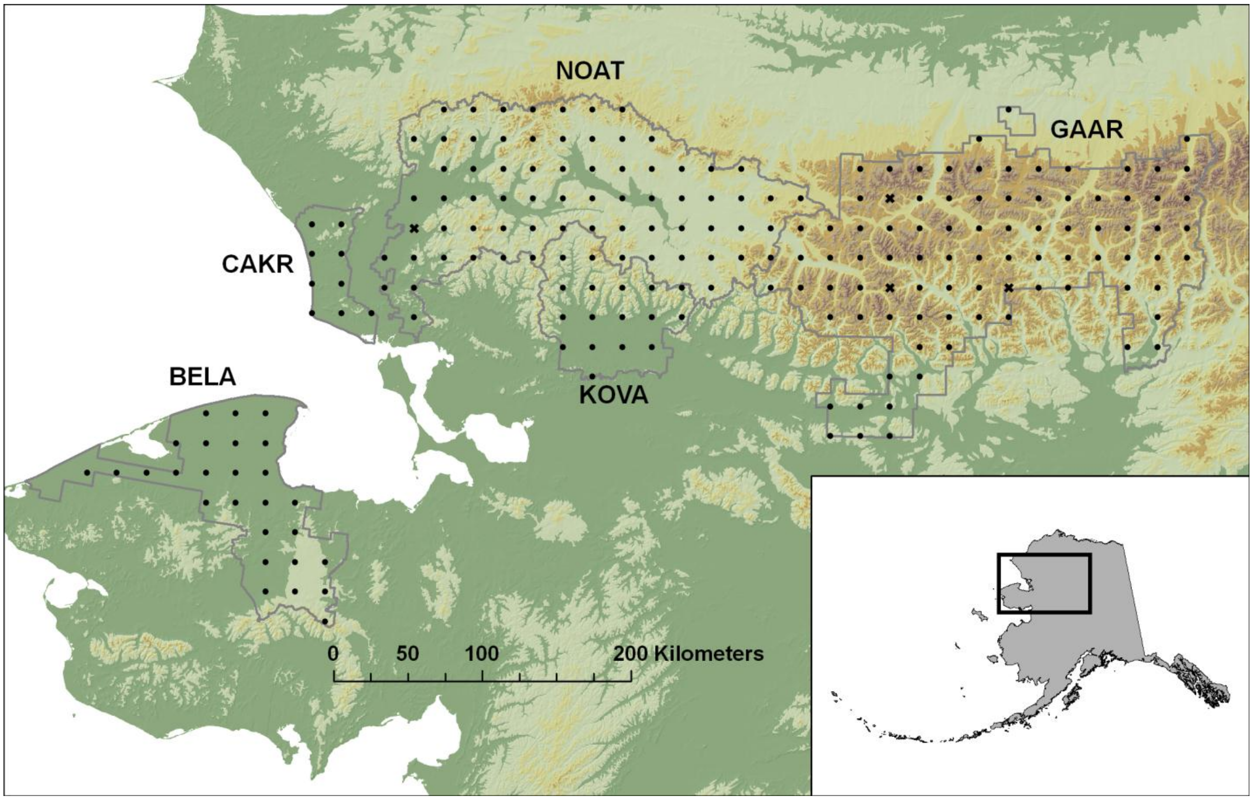


Figure 1. The sample grid of plots spaced at 20-km intervals across the NPS Arctic Inventory and Monitoring Network (ARCN). ARCN consists of 5 NPS units: Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park and Preserve (GAAR), Kobuk Valley National Park (KOVA), and the Noatak National Preserve (NOAT). The four plots marked with an “x” were not sampled due to missing images.

The vegetation of ARCN consists mainly of arctic tundra, with spruce and birch forest (taiga) at low elevations in the southern part of the interior parks (Fig. 2). Low shrub and herb-dominated vegetation occurs in taiga wetlands and burned areas in the south, and elsewhere on tundra throughout the network at low elevations. Sparse alpine vegetation and barrens dominate at high elevations. Tall shrub communities are most common on floodplains and near treeline. They occur in small patches at low to moderate elevations throughout the network, with only their most extensive occurrences shown in Fig. 2.

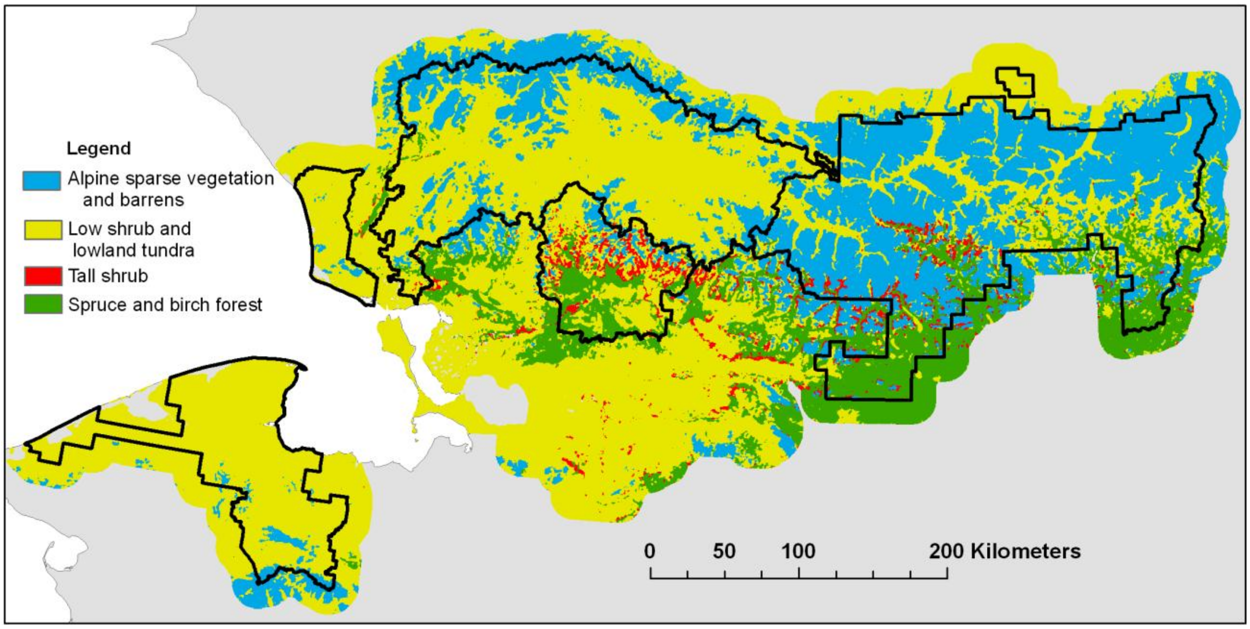


Figure 2. Generalized vegetation of ARCN (from Jorgenson et al. 2009).

Wildfires are fairly common in the more densely vegetated, lower-elevation parts of ARCN. The sample plot locations were intersected with the best available fire perimeter map to identify fire-affected plots (Table 1). The fire perimeter information reaches back to the 1940s, but is incomplete prior to 1970. Four of the 206 plots burned in the 1970s, just prior to our first photo dates, and two burned during the sample interval.

Table 1. Wildfires at ARCN sample 20 km grid sample plots[1]

Plot	FireName	FireYear	Image Years	Environment
GAAR_-7_188	SELBY LAKE	1971	1979, 2009	Tundra-forest ecotonal shrub
BELA_-41_177	KUGRUK HI	1977	1980, 2008	Tussock tundra
NOAT_-37_196	OTZ NNW 38	1977	1979, 2008	Tundra low shrub
NOAT_-37_198	OTZ NNW 38	1977	1979, 2008	Tundra wetland
GAAR_-1_190	132614	1991	1981, 2009	Riverine barrens and shrub
NOAT_-35_200	Uvgoon Creek	2004	1979, 2008	Tundra shrub

[1]From the Alaska interagency map of historical fire perimeters (AFS 2012).

Methods

Image Sources

Three images sources were used in this study: AHAP color-infrared aerial photographs, IKONOS satellite images, and small-format digital color aerial photographs (Table 2). The AHAP images are high-quality, nearly cloud-free, high-altitude, color-infrared aerial photographs taken with a traditional large-format film mapping camera. They were scanned at 14 µm (1800 dpi; about 0.9 m in ground units) by the US Geological Survey EROS Data Center. I chose a scan resolution slightly finer than the grain of the film in order to preserve all detail. Less detail is discernable on the scanned AHAP photographs than the 1 m-resolution IKONOS images. I estimate that the AHAP photos have an effective resolution of 1 to 2 m. The AHAP photographs were taken over the period 1977 to 1985. Their coverage of ARCN is nearly complete; just two of the possible systematic grid points were not covered, one due to clouds and another due to a gap between photo frames. Color-infrared photos display near-infrared reflected light as red on the photo, red reflected light as green on the photo, and green reflected light as blue on the photo. Dense deciduous vegetation is highly reflective in the near-infrared band, giving these areas a bright red color. The near-infrared color band is less affected by haze than visible bands, and it is useful for discerning different vegetation types that appear uniformly green on natural color photographs.

Table 2. Image source for analysis of landscape change

Image Type	Dates	Image Type	Scale/Resolution	Approximate Footprint	Note
AHAP (Alaska High-Altitude Aerial Photography) color-infrared aerial photographs	June, July, August, 1977 to 1985	Large-format (9 inch by 9 inch negative) color-infrared aerial photography	Original negatives: approximately 1:60,000; Scanned at 14 µm (1800 dpi, approximately 0.9 m resolution)	12 X 12 km	The effective resolution ("grain") of the photographs is slightly greater than the scan resolution, approximately 1-2 m
IKONOS satellite images	June, July, August, Sept 2006 to 2009	4-band multispectral Blue 0.445-0.516 µm Green 0.506-0.595 µm Red 0.632-0.698 µm Near IR 0.757-0.853 µm	4 m multispectral pixels, pan-sharpened to 1 m	Variable, 12 to 20 km by 6 to 14 km	Orthocorrected using image parameters and the 60 m National Elevation Dataset (NED) digital elevation model (DEM)
Small-format vertical digital aerial photographs	August, Sept 2008 to 2010	35 mm color digital photography NIKON D2X (23.7 x 15.7 mm sensor; 4288 x 2848 pixels) and NIKON D700 (36 x 23.9 mm sensor; 4256 x 2832 pixels)	0.15 to 0.20 m	400 to 600 m by 600 to 900 m	

Small-format, natural color, digital aerial photographs were collected in 2008-2010 to cover each sample grid point. These photos were shot with a 35 mm camera (which had a sensor 24 or 36 mm wide, depending on the camera model used; Table 2); these photos are termed "small-format" in contrast to the AHAP photos, which were shot with a specialized aerial photography mapping camera that exposes 9 x 9 inch (230 by 230 mm) film. The small-format photographs were shot with approximately 60% overlap to allow stereo 3D viewing. The photographs are mostly summer (leaf-on, green) or early fall (leaf-on with some color change); some photographs from Sept 2010 have mostly senesced, leaf-off vegetation.

The time interval separating the images varied from plot to plot, from 23 to 33 years (Table 3). The median time interval was 30 years.

Orthorectified high-resolution IKONOS multispectral satellite images (Table 2) are available for most of ARCN.

Table 3. Time interval between images used for change analysis.

Interval, yrs	Count of plots
23	12
24	2
25	2
27	7
28	41
29	37
30	37
31	40
32	25
33	4

Sampling

There are 210 systematic grid points in ARCN, of which 4 were missing data: two had no AHAP coverage and two lacked both IKONOS and small-format images (Fig. 1). Thus the trend analysis was completed for 206 grid points. Five of the 206 grid points lacked small-format photos, so the trend analysis there was made using AHAP and IKONOS only. For the remaining 201 grid points, I used AHAP for the start point in the trend analysis and both small-format (primarily) and IKONOS images for the second point in the trend analysis.

The sample area was a 4-ha circle centered at each ARCN 20-km grid point. The 4-ha circle is referred to as the "plot" in this report. A 4-ha circle has a radius of 112.84 m, which is about the largest size that can be consistently fit inside a single frame of our small-format photography. A plot of this size usually has a simple slope and aspect, and thus the plot boundaries can be projected fairly accurately onto photographs that have been georeferenced but not orthorectified. When an image is georeferenced, it is simply rotated, rescaled, and skewed (distorted into a parallelogram, if necessary) to best match a reference image (in our case, the orthorectified IKONOS image). Georeferencing corrects for scale and simple perspective distortions, but not for complex topographic displacement, which generally does not occur in our small plots.

Both the AHAP and small-format photographs were georeferenced, using ArcMap 10.1 software, to the IKONOS 1-m resolution imagery, which had been orthorectified in ArcMap using the 60 m National Elevation Dataset. Georeferencing was a fairly quick and simple process of locating 3 to 10 tie points between the photograph and the IKONOS image. Tie points were located in order to obtain good georeferencing within the 4-ha sample plot only, not the entire image. The tie points were used to create a first order (affine) transformation of the photograph. Our experience with georeferencing photographs by affine transformation shows that in most cases it is possible to make all landmarks within the 4-ha circular plot match within 5 m linear distance.

Plot-level Change Detection

I examined the two image dates for any changes in land surface cover, vegetation, or landforms. Changes in land surface cover and vegetation are readily expressed as change in area. Since changes in landforms such as river channel migration or lake expansion by thermokarst result in changes in vegetation and land surface cover, these landform changes were recorded as mechanisms associated with change in a land surface cover. Change in ice-wedge polygon morphology, as discussed later, was also assessed.

Plot-level Vegetation and Land Surface Cover

Initial tests of change detection methods showed that it was clearly much easier to identify that a change had occurred between two photo dates (e.g. “shrub increase”) directly by visual comparison of two images than to exhaustively map the feature of interest (e.g. shrub canopies) on both images and then compute change by difference in map area. Thus I compared images from the two dates and classified the type of change in area (percent cover) between the photograph dates of shrubs, trees, barrens, lichens, wetlands, and water as “increase”, “no change”, or “decrease”. For each case of “increase” or “decrease”, the mechanism of change was also noted (Table 4). This list of change mechanisms was revised during the course of the photointerpretation to include all identifiable change mechanisms in the study area. A “no change” determination is, of course, more accurately described as “change not detectable with reasonable certainty”, since some change has undoubtedly occurred. The detectability of change varied irregularly between plots as a function of both image quality and the innate detectability of certain types of change. An example is alder shrub increase, which as a result of the large size and bright color of alders was more detectable than increases in other shrubs.

Plot-level Ice Wedge Polygon Morphology Changes

Ice-wedge polygon changes between high-centered, flat, and low-centered were also recorded for the plot as a whole. A polygon was considered “low-centered” if the center was clearly wetter than the polygon rims (as shown by darker tones on the images); “flat” if the polygon was uniformly colored except for narrow ice-wedge troughs; and “high-centered” if troughs were broad and polygon center higher or visibly drier than the troughs. The relief on high-centered ice-wedge polygons on the recent high-resolution photographs could often be verified in stereo 3D.

Probability Testing

As will be discussed below, observations of "no change" dominated and we are primarily interested in whether the observed counts of "increase" and "decrease" for any given feature differ significantly. Our three change types ("increase", "decrease", and "no change") are modeled by a trinomial distribution. In a Bayesian formulation, the natural prior distribution for a trinomial variable is the Dirichlet distribution, and the posterior distribution is then again Dirichlet. Using an uninformative prior (Jeffrey's) adds 0.5 count to each category, and then the posterior distribution of the probability of each category is the counted (plus 0.5) proportion in that category. Confidence intervals on estimated probabilities, and difference in probabilities can be obtained by sampling from the posterior distribution. Variances (and confidence intervals) on posterior probabilities were estimated with 10,000 independent draws using the "rdirichlet" function in the MCMC pack (Martin et al 2012) of R statistical software (R Core Team 2012) . The 95% confidence interval for the estimated probability of each outcome "increase", "no change", and "decrease"), and for the difference between "increase" and "decrease", was computed using quantiles from the 10,000 random draws from the posterior distribution. We conclude that our observed count of "increase" plots for some feature differs from the number of "decrease" plots if the confidence interval for the difference in their estimated probabilities does not contain zero.

Table 4. Land cover change types and mechanisms.

Change type	Change mechanism
Shrub_increase	increase on tundra
	post-fire succession
	floodplain succession
	increase on wetland
	other primary succession
Shrub_decrease	fire
	floodplain erosion
	succession to trees
	wetland expansion
Tree_increase	increase on tundra
	post-fire succession
	floodplain succession
	increase on wetland
	other primary succession
	infilling below treeline
Tree_decrease	fire
	floodplain erosion
	wetland expansion
Lichen_increase	succession
Lichen_decrease	fire
	erosion
	wetland expansion
	shrub increase
	herbivory/other
Barren_increase	fire
	floodplain erosion
	snowfield/icing expansion
	mass movement
Barren_decrease	floodplain vegetation increase
	vegetation increase on snowfield/icing
	upland vegetation increase
Wetland_increase	thermokarst
	non-thermokarst water level rise
	paludification
Wetland_decrease	thermokarst
	non-thermokarst water level drop
Water_increase	thermokarst
	non-thermokarst water level rise
	stream channel migration
Water_decrease	outlet incision
	non-thermokarst water level drop
	stream channel migration

Ecological Type Composition of the Plots

To estimate the area involved in the various vegetation transitions that occurred between the two photo dates, the ecological types ("ecotypes") in each sample plot on each photo date were classified by the scheme developed for the ARCN Ecological Land Survey and Land Cover Map (Jorgenson et al. 2009). This is a land cover classification scheme with 44 classes that synthesize vegetation, soil, and site information; spectrally based land cover classes are further subdivided based on landform information, e.g. white spruce forest is divided into riverine and upland variants. This classification scheme is based on many field plots (n = 763) and allows direct up-scaling to the ARCN-wide ecotype map.

The ecotype composition of each plot was estimated using a hexagonal grid (Fig. 3). Hexagons with 34 m spacing (37 cells per plot) were chosen as a good compromise between precision of estimates (more cells is better) and ease of classification (fewer cells is better). Each hexagon covers 867 m^2 area, which is quite similar to the 900 m^2 of the Landsat Thematic Mapper pixels for which the classification was devised; each cell covers about 2.5% of the overall plot circle area. The dominant ecotype was determined for each hexagon. The composition of the plot could then be computed from the count of hexagons of each ecotype.

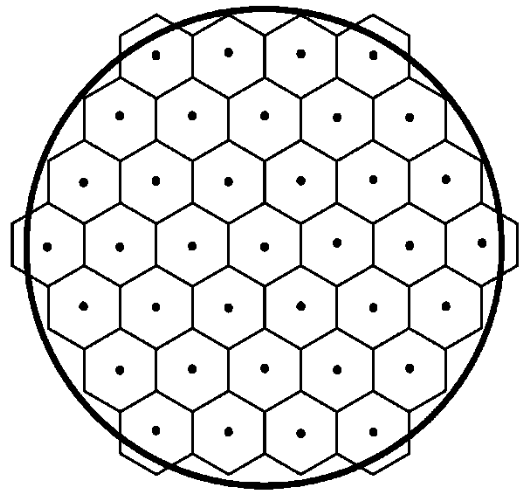


Figure 3. Four-hectare sample plot with a hexagonal grid of subsamples for vegetation and ice-wedge classification.

The predominant ecotype (Jorgenson et al., 2009) was assigned to each hexagon. The ice-wedge morphology class (“low-centered”, “flat”, or “high-centered”; see text for definitions) was assigned to any two hexagon center points separated by a visible linear feature identified as an ice wedge.

Ecotypes were difficult to assign with certainty, especially for the AHAP photographs (because of their lower resolution). To avoid false change detection due to errors in ecotype identification, I first determined the ecotype on the recent, high-resolution images. Then I assumed that the ecotype was the same on the AHAP photographs unless there was convincing evidence for change as identified in the previous section “Plot-level Change Detection”. Ecotype assignments were verified by viewing the small-format photographs in stereo 3D, and by consulting the nearly simultaneous IKONOS images displayed in color-infrared color scheme (which matches the color scheme of the AHAP aerial photographs).

Ice Wedge Polygons Areal Coverage

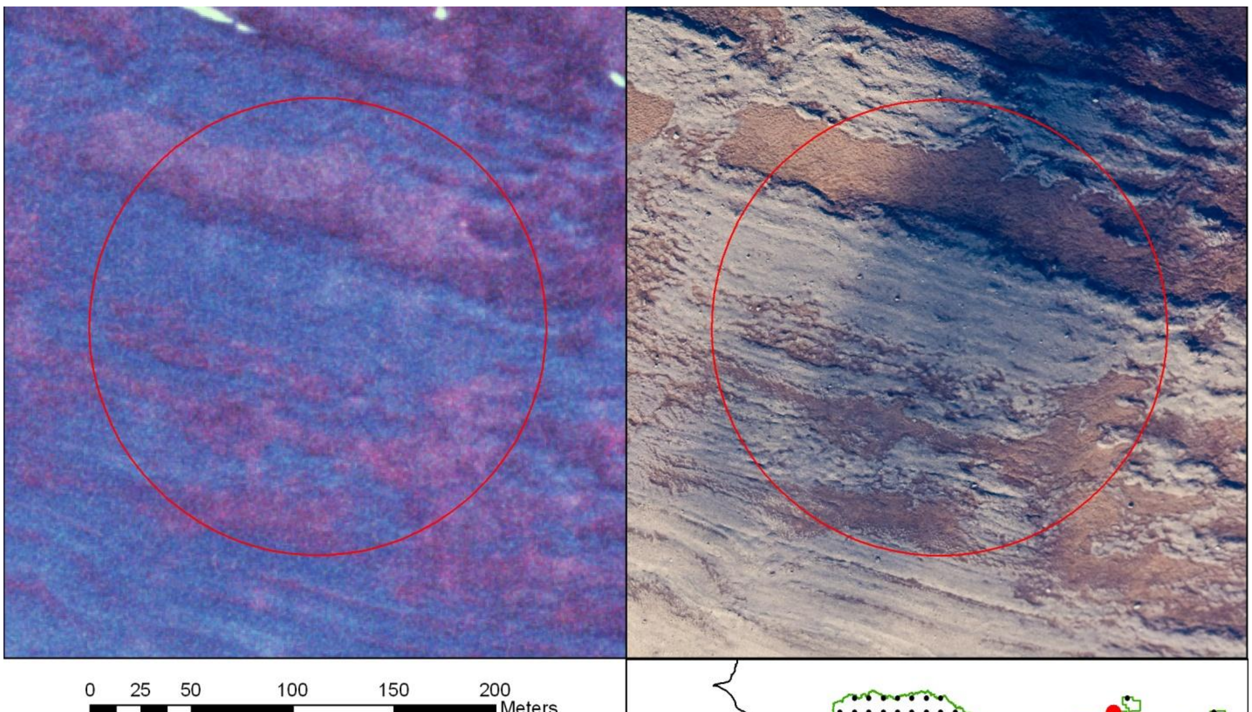
Ice wedge polygon classes were also tallied using the hexagonal grid. An ice-wedge class was assigned to any two hexagon center points (Fig. 3) that were separated by a linear feature judged to be the result of an ice-wedge. Classes were “low-centered”, “flat”, and “high-centered” as defined in the previous section.

Analysis of Environmental Factors

The detected changes were compared to environmental factors at the plots. Elevation, slope steepness, and slope aspect for each plot were determined from the National Elevation Dataset (60 m resolution; Gesch et al. 2009). Temperature estimates at each plot for the period 1971-2000 are from the PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 16 Sept 2009.

Results and Discussion

The majority of plots (157 out of the possible 206: 76%) displayed no change in any of the features studied over the approximately 30-year study interval (Fig. 4). The plots which did change were located predominantly in the lower elevation areas (Fig. 5). Nearly half of the plots (29 out of 61) below 305 m (1000 feet) elevation displayed a change in one or more features, while none of the 33 plots above 1067 m (3500 feet) displayed any detectable changes. Lower elevations in ARCN have denser vegetation, and this is where wildfires occur. Also, most of the river floodplains, ponds and lakes, and ice-rich sediments subject to thermokarst are also located at low elevations. High elevations are sparsely vegetation and dominated by bedrock or coarse-rubble substrates.



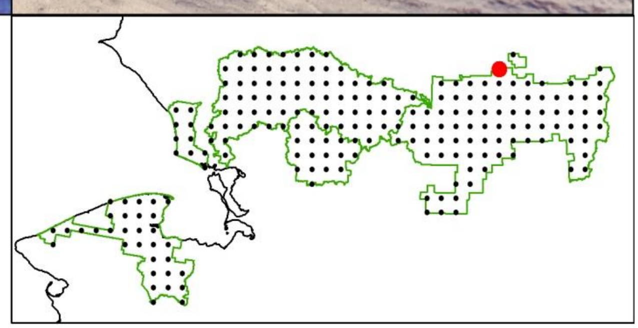


Figure 4. A plot that changed little between 1978 (AHAP color-infrared photo on the left) and 2010 (small format, natural color photo on the right). The vegetation distribution on this plot is strongly controlled by bedrock outcrops (which are largely barren of vegetation) and pockets of soil with herbs and low shrubs. (Plot GAAR_3_206; location shown in red on the inset map.)

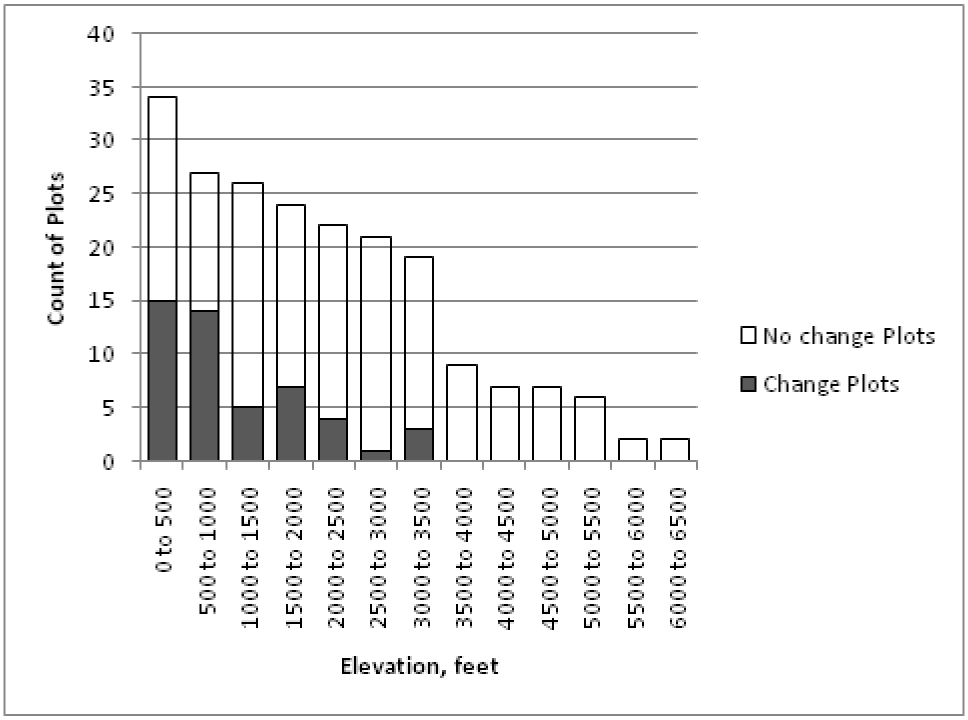


Figure 5. Distribution of plots displaying vegetation and geomorphic changes recorded during an approximately 30-year period from 1980 to 2010.

Shrubs

Shrubs increased on 23 plots and decreased on just 2 plots (Table 5). The main causes of shrub increase were "increase on tundra" and "floodplain succession". Minor shrub increases also occurred as a result of drying of wetland (one plot in KOVA), revegetation of a thaw slump ("other primary succession"; one plot in NOAT), and "post-fire succession" (one plot in GAAR). The last case was in the lowland forest-tundra ecotonal area of southwestern GAAR, where shrubs continued to increase for decades after a 1971 fire; this is an ambiguous case that may combine post-fire effects and climate-related shrub increase on tundra. The shrub decreases were due to river channel migration in one case and post-fire succession to trees in another.

Table 5. Summary of changes in shrub cover

Shrub Change	Shrub Mode of Change	Count of Plots
increase	increase on tundra	15
increase	floodplain succession	5
increase	increase on wetland	1
increase	other primary succession	1
increase	post-fire succession	1
decrease	floodplain erosion	1
decrease	succession to trees	1

Shrub increase on tundra

Shrub increase on undisturbed tundra was observed in at least one plot in all park units, though predominantly in NOAT (8 plots) and CAKR (3 plots out of just 10 in this park unit; Figs. 6 and 7). Shrub increase detected on tundra usually involved alders; this is in part due to the fact that alder is most visible on AHAP photos due to its large size. Shrub increase occurred on slopes ranging from 1° to 18° and on all slope aspects. Elevations ranged from about 9 m (30 ft) above sea level in southwestern NOAT to about 950 m (3100 ft) above sea level in GAAR. July estimated mean temperatures at tundra shrub-increase plots ranged from 11 to 14 °C, which is clearly warmer than the average for all plots but excludes the very warmest (Fig. 8). In ARCN most areas with estimated July mean temperatures above 14 °C are forested, and thus shrub increase onto tundra is not possible. Shrub increases on undisturbed tundra were not noted in areas with colder summers (estimated mean temperatures of 4 to 10 °C). If we take all plots without forested ecotypes as our pool of plots where increase of shrubs on tundra is possible (n = 178), the 15 plots with shrub increase on tundra represent 8% of possible plots and is significantly different from the zero plots that showed a shrub decrease on undisturbed tundra (Table 6). While shrub increase on tundra was not uncommon, many tundra plots showed remarkably stable shrub cover over the study time interval (Fig. 9).

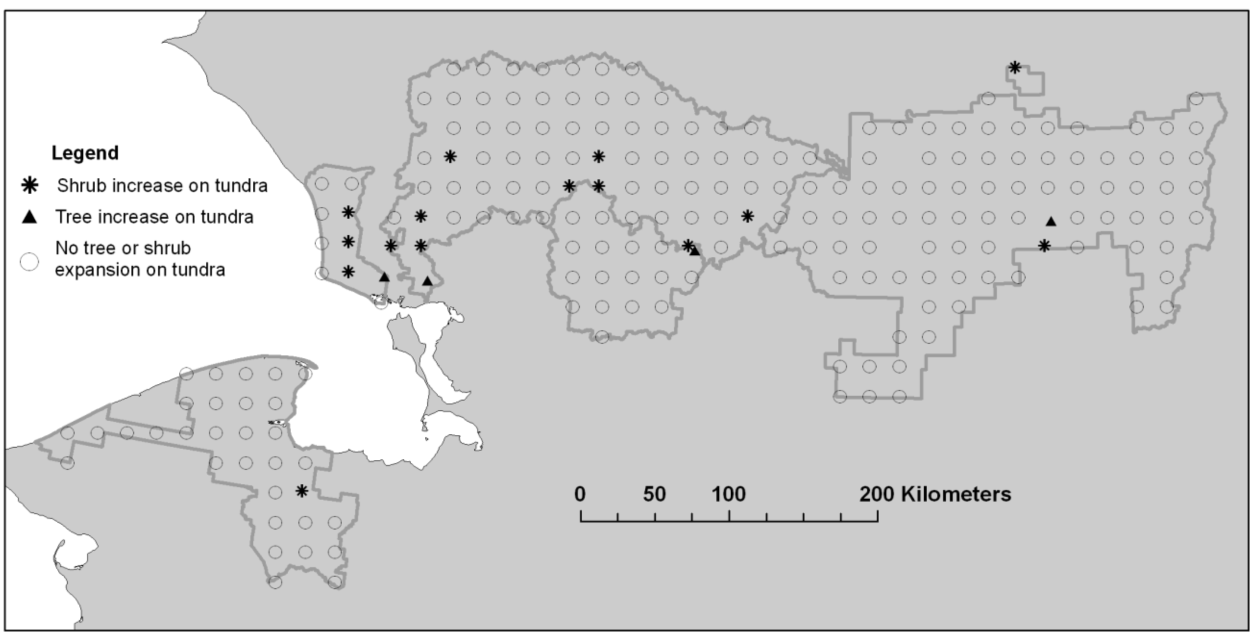
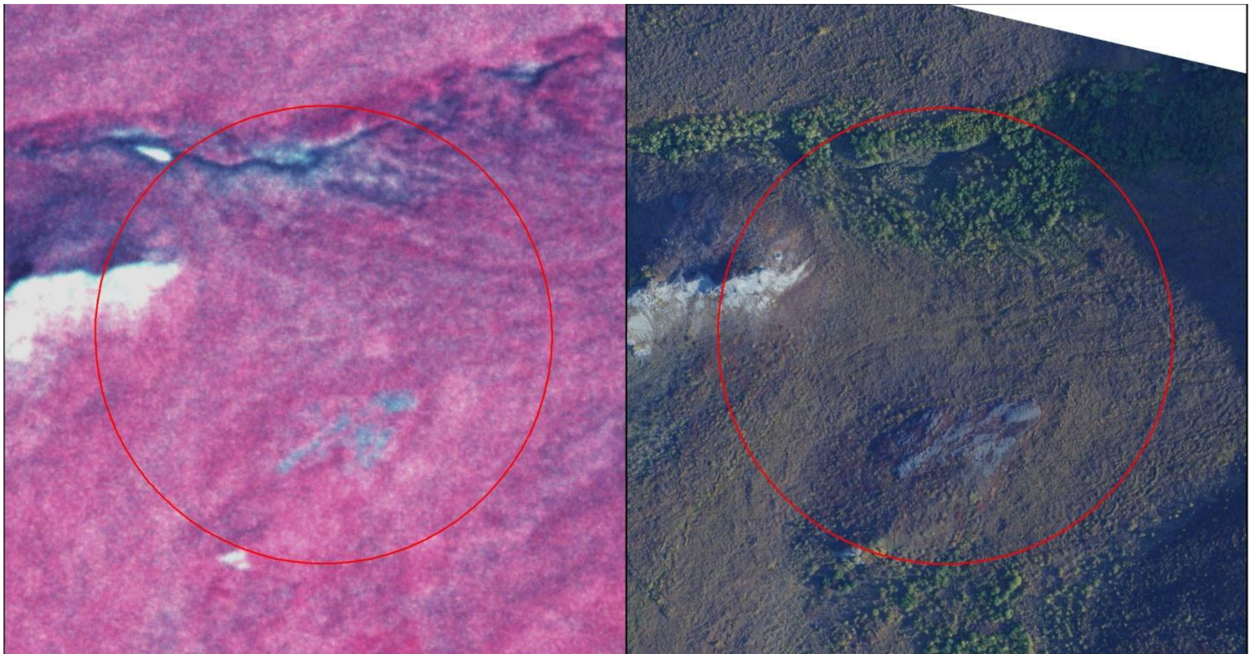


Figure 6. Plots with shrub or tree increase on tundra.



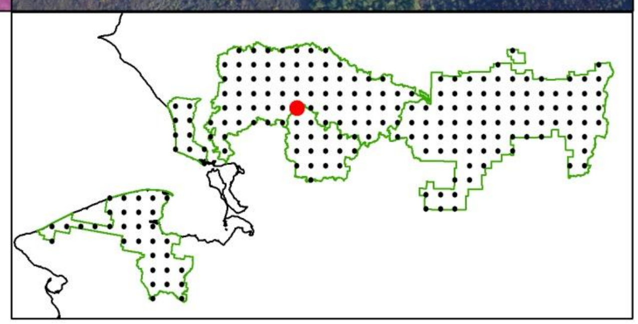


Figure 7. Tall shrub increase on tundra. An area of mostly herbaceous and low shrub vegetation in 1979 (AHAP photo, left) was covered by tall shrubs in 2008 (small-format photo, right). The grayish area along the creek on the AHAP photo was probably a snow bed, note the small residual patch of snow (on 12 July) along the creek just outside of the plot to the left. (Plot NOAT_-25_200.)

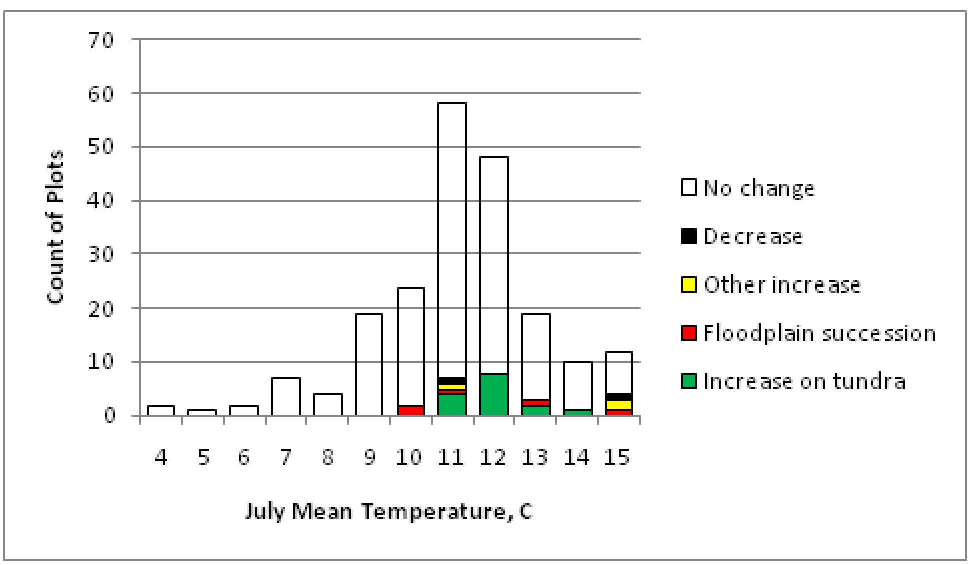
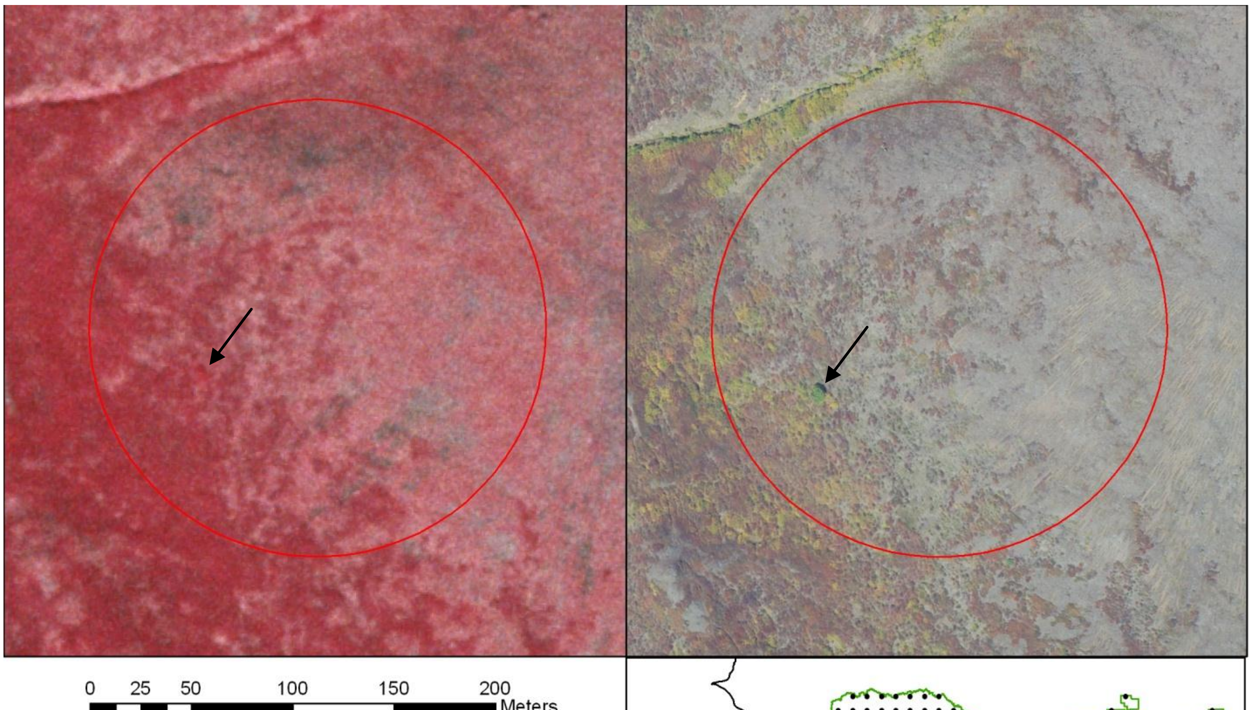


Figure 8. Frequency of plots with shrub cover change versus estimated mean July temperature (n = 206, rounded to the nearest integer; temperature estimates for the period 1971-2000 are from the PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 16 Sept 2009

Table 6. Probability analysis of the observed sampling outcome for shrub increase on tundra

Change	Count of plots	Probability[1]
Increase	15	0.086 (0.050 - 0.131)
No change	163	0.911 (0.866 - 0.947)
Decrease	0	0.003 (0.000 - 0.014)

[1]Mean and 95% confidence interval (2.5^{th} to 97.5^{th} percentile) of 10,000 trials of a Dirichlet distribution for the observed counts. The 95% confidence interval for the difference between “Increase” and “Decrease” is 0.046 to 0.129, which does not include zero and thus indicates a significant difference.



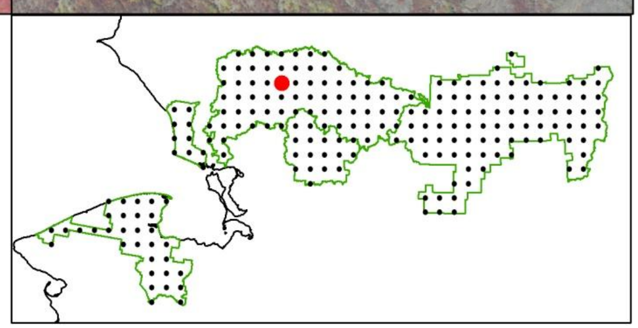


Figure 9. Plot with tundra shrubs that changed little between 1980 (AHAP color-infrared photo, left) and 2008 (small-format natural color photo, right.). On the AHAP photo, shrubs are dark red (densely vegetated), and areas with less dense vegetation are lighter colored. On the late summer natural color small-format photo, willow shrubs are yellow and birch shrubs are reddish. The one large alder shrub visible in 2008 (arrow, green spot) can be located on the 1980 photo (arrow) (Plot NOAT_-27_204.)

Shrub change on floodplains

Shrubs increased on 5 plots by floodplain succession and decreased on one plot due to riverbank erosion. A total of 21 plots sampled floodplain environments, and thus 15 showed no shrub change. Shrub increase was mainly by infilling of sparse shrub communities. Because of the small sample size, the apparent increase in floodplain shrubs is not highly significant: the 95% confidence intervals for the estimated prior probability of “decrease” and “increase” substantially overlap, and the 95% confidence interval for the difference between the two ranges from -0.032 to 0.395 (Table 7). In other words, the "true" probability of increase and decrease could be similar, and the observed difference in counts could be due to chance.

Table 7. Probability analysis of the observed sampling outcome for shrub change in riverine environments

Change	Count of plots	Probability[1]
Increase	5	0.244 (0.094 - 0.436)
No change	15	0.689 (0.487 - 0.859)
Decrease	1	0.067 (0.005 - 0.196)

[1]Mean and 95% confidence interval (2.5th to 97.5th percentile) of 10,000 trials of a Dirichlet distribution for the observed counts. The estimated probability of "increase" is greater than "decrease", but the confidence intervals for these two estimates substantially overlap, and the 95% confidence interval for the difference between the two is -0.032 to 0.395. Since this latter interval overlaps zero we conclude there is no significant difference between the probability of increase and decrease.

Trees

Trees increased on 15 plots and decreased on 2 (Table 8). The most common reason for tree increase was post-fire succession, which occurred on 10 plots, all in GAAR and KOVA. No fires burned forested plots during the sample period. Succession is a gradual and prolonged process that occurs for decades after a fire, while fires in interior Alaska represent relatively infrequent but drastic reductions in tree biomass. Thus for a relatively small forested area such as ours, many plots with minor successional tree increases and none with complete tree loss by fires indicate a local increase in tree biomass during the sample period, but are not conclusive evidence for a long-term change in the balance between fire and forest growth.

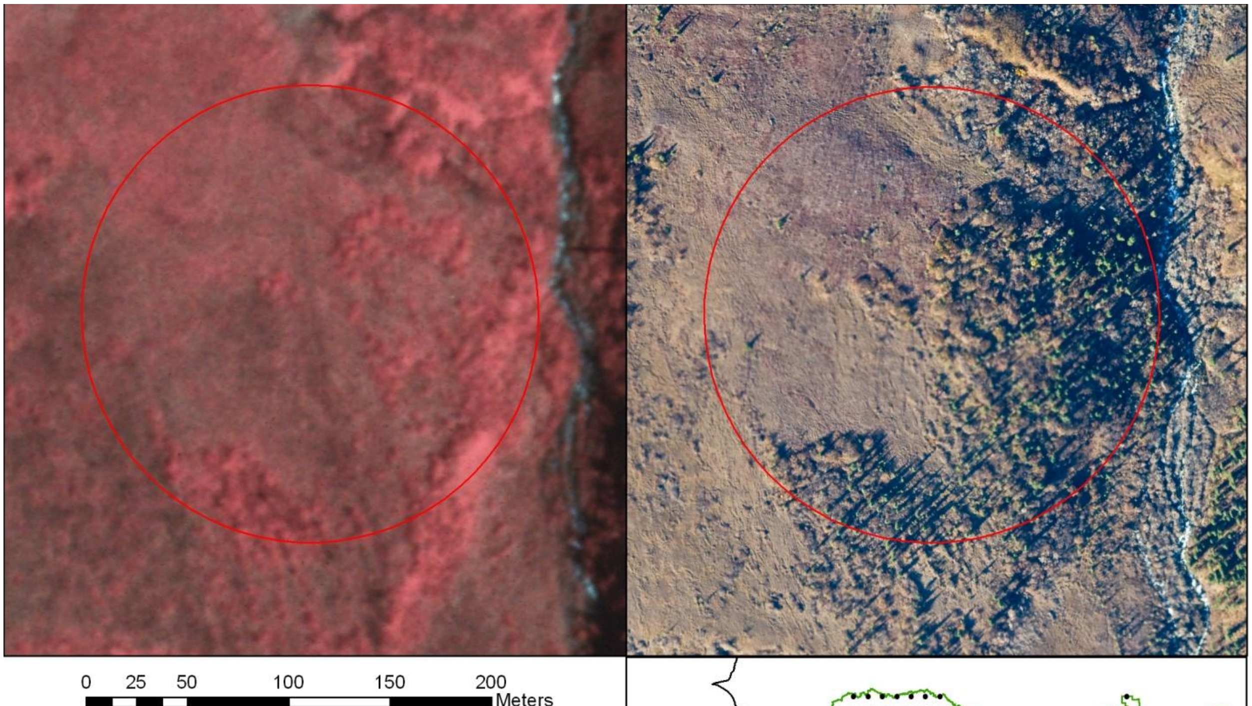
One plot showed tree colonization onto drying wetland, which can be viewed as the complement of the one plot with tree loss by thermokarst wetland formation described below.

Trees colonized tundra on 4 plots, one plot in each of CAKR, GAAR, KOVA, and NOAT (Fig. 6). In all cases this was white spruce colonization of tundra on upland slopes (Fig 10). Estimated July mean temperatures at the four plots with tree increase on tundra were 12 to 14 °C, which is on the warm end of our available environments (compare to Fig. 8 for shrubs).

Tree declines were due in one case to a river channel migration that eroded away a bit of poplar forest, and in the other to thermokarst conversion of lowland black spruce forest to unforested wetland.

Table 8. Summary of changes in tree cover

Tree Change	Tree Mode of change	Count of Plots
increase	increase on tundra	4
increase	increase on wetland	1
increase	post-fire succession	10
decrease	floodplain erosion	1
decrease	wetland expansion	1



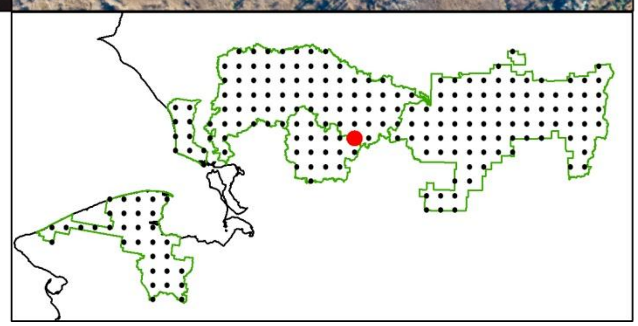


Figure 10. Tree and shrub increase in tundra. In an area near treeline with tall shrubs in 1978 (AHAP photo, left), the shrub cover increased and white spruce trees grew up among them by 2010 (small-format photo, right). (Plot KOVA_-17_196.)

No plots intercepted poplar forest beyond the spruce limit. Poplars occur locally on floodplains in NOAT and GAAR beyond the spruce limit and are of interest for possible increase as the climate warms.

Lichens

No lichen change was detected on any photograph pairs. The most readily visible change in lichen cover would be a decrease by wildfire. As mentioned previously, only two plots burned during the study time interval (Table 1). Neither of these plots was rich in lichens before the fire. A major shrub increase into a lichen-rich habitat could also cause lichen decrease, but none of our shrub increases were in lichen-rich habitats. A marked increase in lichen cover would be most likely to occur by post fire succession on a previously lichen-rich site. However, 50 years or more (i.e. longer than our study interval) is required to re-establish a dense lichen cover after fire in ARCN (Swanson 1996a, 1996b).

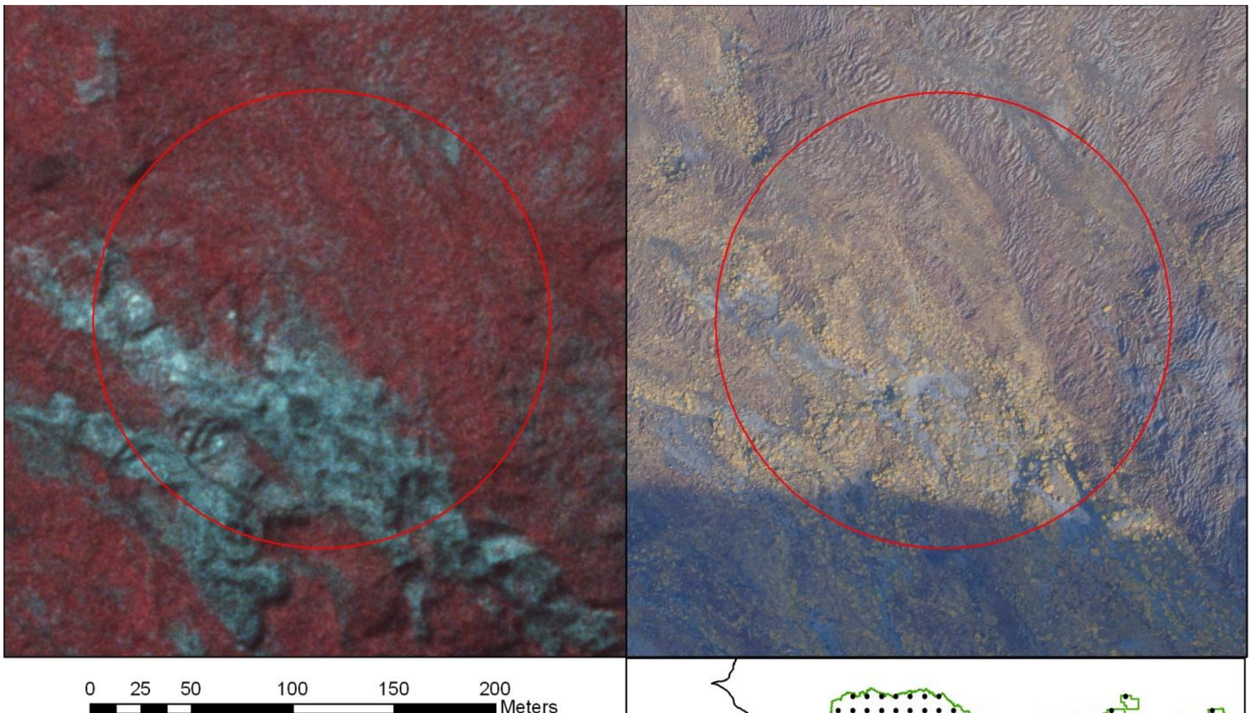
Barren areas

Very few plots showed a change in area covered by bare ground or rock (Table 9). On the 10 plots where riverine barrens occurred, 1 showed a decrease in barren area due to vegetation increase and 2 showed an increase in barrens due to erosion of vegetated areas by the river. On one upland plot the barren area decreased as a recent retrogressive thaw slump visible on the

1977 photograph was revegetated (Fig. 11). None of the 59 plots with true alpine barrens showed any change in barren area.

Table 9. Summary of changes in barren areas

Barrens change	Barrens Mode of Change	Count of Plots
increase	floodplain erosion	2
decrease	floodplain vegetation increase	1
decrease	upland vegetation increase	1



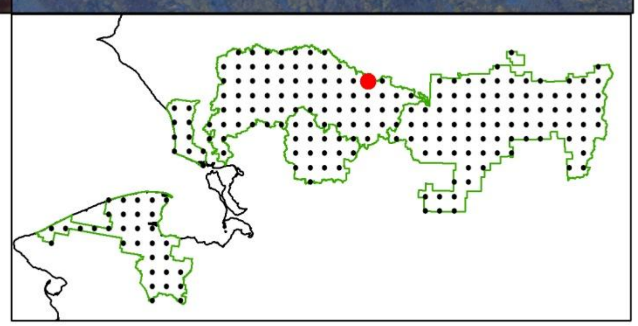


Figure 11. Decrease in barren area by upland vegetation expansion (primary succession). A fresh retrogressive thaw slump in 1977 (AHAP photo, left) was mostly revegetated with shrubs by 2008 (small-format photo, right). (Plot NOAT_-15_204.)

Wetlands

Changes in wetland area occurred on just 6 plots (Table 10). "Paludification" (2 plots) here is the conversion of lake or pond water into wetland, which occurred by peat accumulation (paludification in the strict sense) and by minor drops in the pond water level. Wetland expanded by thermokarst on two plots: one by subsidence of black spruce forest into wet bog and another by subsidence and enlargement of a tundra water track. The number of plots which could be susceptible to changes in wetland area is approximated by the number of plots with lowland, wetland, or tussock tundra ecotypes (91 plots) or slopes less than 5° (87 plots). A trinomial test on the former (n = 91) shows that the probability of wetland decrease (2 plots) vs. increase (4 plots) did not differ significantly (Table 11).

Table 10. Summary of changes in wetland area

Wetland change	Wetland mode of change	CountOfPoint
increase	paludification	2
increase	thermokarst	2
decrease	non-thermokarst water level drop	2

Table 11. Probability analysis of the observed sampling outcome for change in wetland area

Change	Count of plots	Probability[1]
Increase	4	0.049 (0.016 - 0.099)
No change	85	0.925 (0.864- 0.969)
Decrease	2	0.027 (0.004 - 0.068)

[1]Mean and 95% confidence interval (2.5th to 97.5th percentile) of 10,000 trials of a Dirichlet distribution for the observed counts. The estimated probability of “increase” is greater than “decrease”, but the confidence intervals for these two estimates substantially overlap, and the confidence interval for the difference between the two is -0.032 to 0.080. Since this latter interval overlaps zero we conclude there is no significant difference between the probability of increase and decrease.

Surface Water

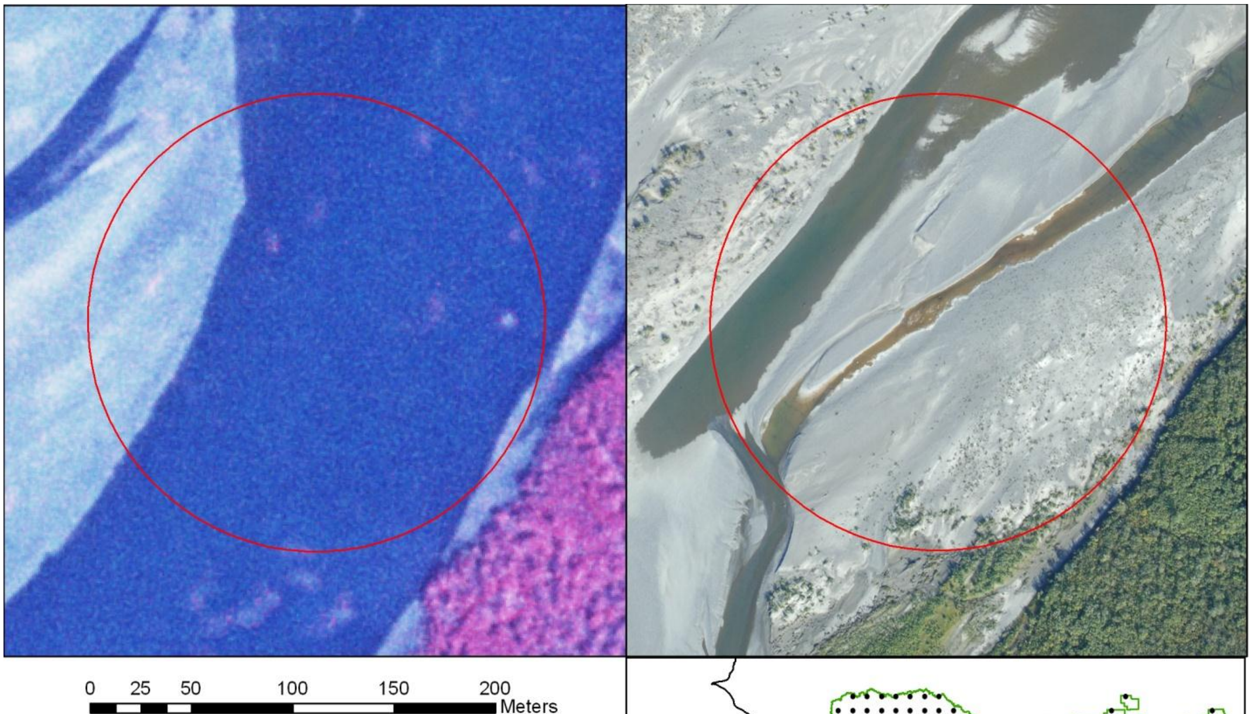
The area of water increased on 8 plots and decreased on 4 plots (Table 12). This was out of a total of 29 plots that had surface water ecotypes (16 plots with the “riverine water” ecotype and 13 plots with the “lowland lake” ecotype).

Table 12. Summary of changes in water area

Water Change	Water Mode of Change	Count of Plots
increase	stream channel migration	2
increase	thermokarst	6
decrease	outlet incision	1
decrease	non-thermokarst water level drop	2
decrease	stream channel migration	1

Changes in river water surface area

One of the plots with the "Riverine water" ecotype showed a decrease in water area and 2 showed an increase in water area, both due to stream channel migration. These results reflect the way normal fluvial processes occasionally cause channels to move into or out of a plot (Fig. 12). Also, river levels can vary between photo dates due to season and weather.



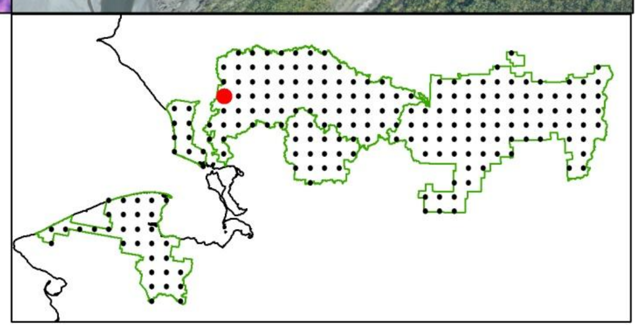
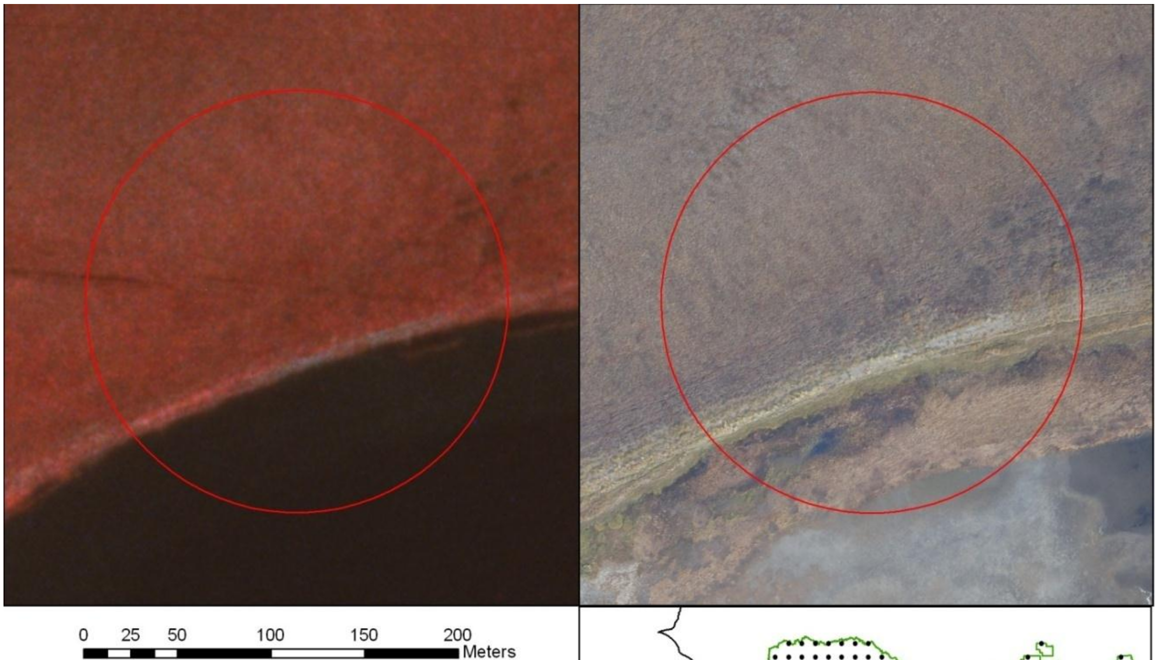


Figure 12. Change in water and barrens by river channel migration. The main channel of the Noatak River flower through the plot in 1979 (AHAP photo, left). In 2008 (small-format photo, right) the main channel had moved, leaving a minor channel and revegetating sandbars in the plot. (Plot NOAT_-35_202.)

Changes in lake and pond surface area

The area of one lake decreased by incision of its outlet (Fig. 13). On 6 plots the area of water increased by thermokarst processes (Fig. 14). This apparent preponderance of lake increase is a bit misleading, because the rather gradual process of lake expansion, evidenced by the 6 plots, is offset by rare but often catastrophic lake drainage events. A better picture of the balance between lake expansion and lake drainage in ARCN will be provided by another project from this vital sign, analysis of the area surface water in ARCN using Landsat data.



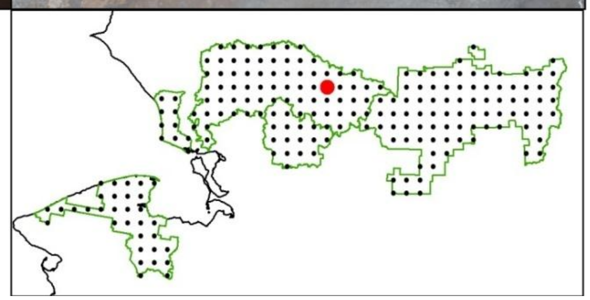
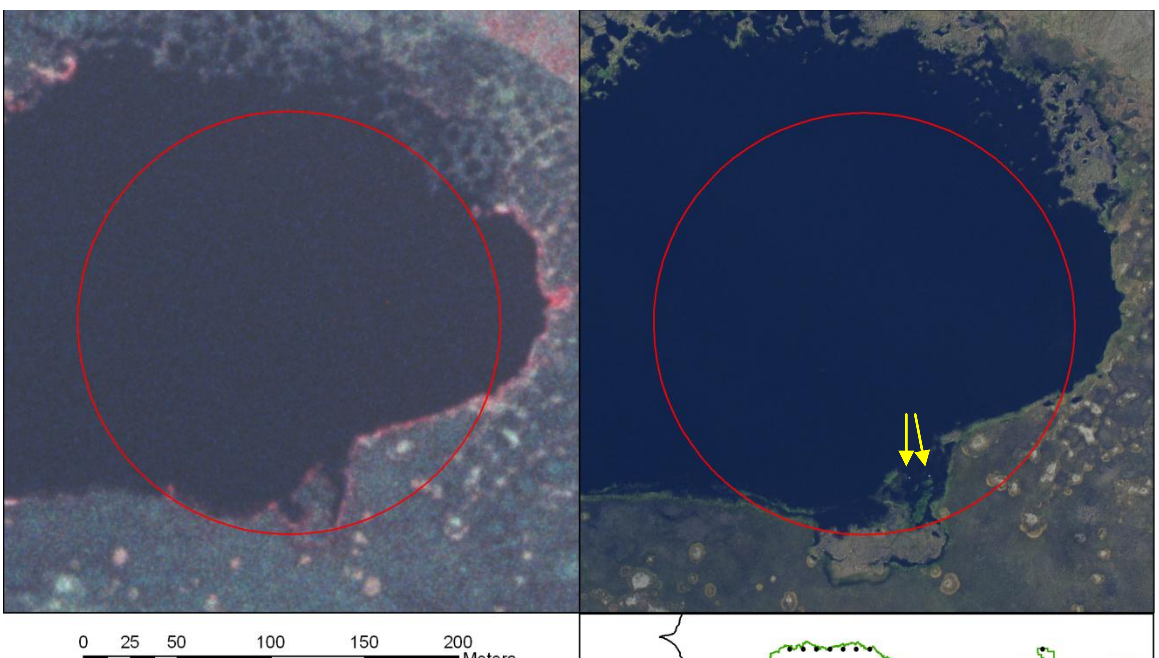


Figure 13. Lake level drop due to incision of the outlet and partial drainage. Water on the lower part of the plot converted to herbaceous wetland. Plot NOAT_-17_202



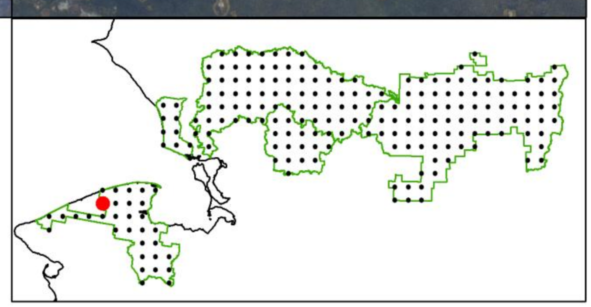


Figure 14. Lake expansion by thermokarst between 1985 (AHAP photo, left) and 2008 (small-format photo, right). The lake expanded southward in the middle part of the plot, increasing the area of open water. Two tiny white specks (arrows) are swans that probably nested nearby. Plot BELA_-51_185.

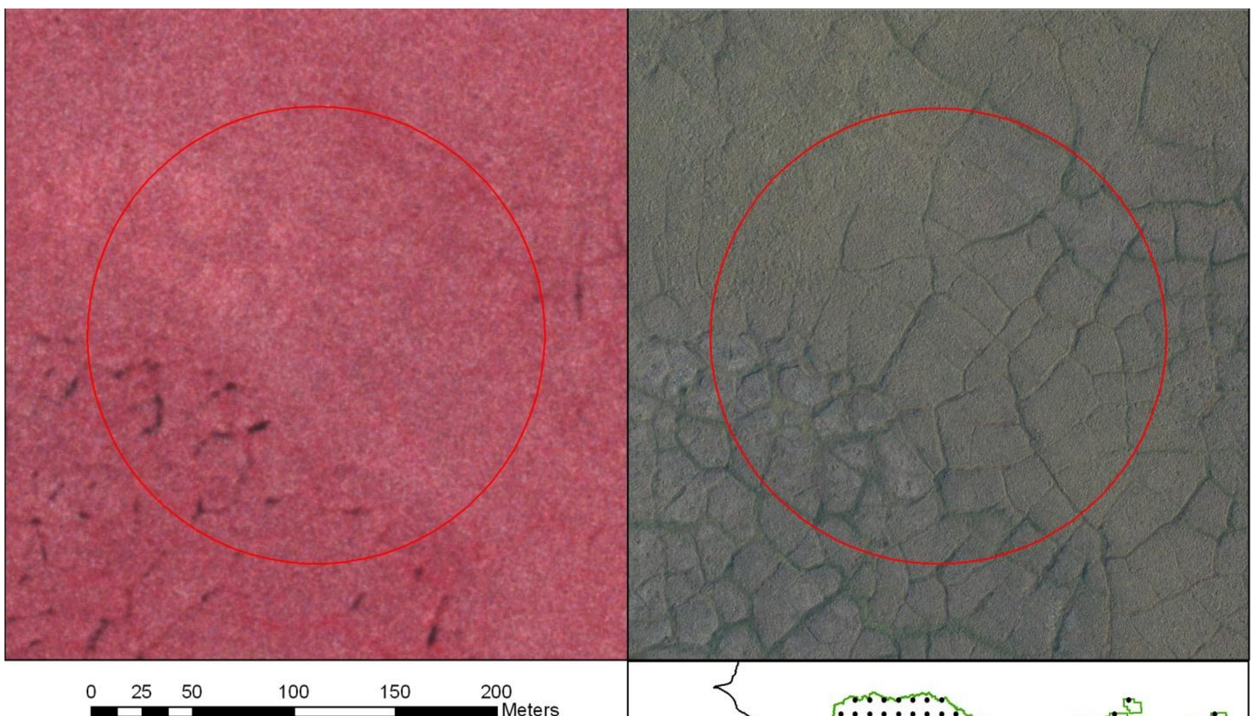
Ice Wedges

Ice wedge polygons were noted in 27 plots, all in lowland areas. Two of these plots showed a detectable change in ice wedge polygon morphology, from flat to high-centered. This transition occurs when wedges melt due to permafrost thaw. In terms of plot area as estimated by the hexagonal subplot classification, 8.3% of the total plot area in ARCN was covered by ice wedge polygons, and they had mainly flat morphology (Table 13). No transitions from high-centered to flat or low-centered were noted, though it is unlikely that this type of transition could be detected by our methods over a 30-year period. The formation of new ice-wedge polygons from unpatterned ground can be fairly rapid with permafrost formation in newly drained lake basins (Mackay and Burn 2002), but this situation did not occur on any of our plots.

Table 13. Summary of ice wedge polygon morphology[1]

Ice WedgeClass	Proportion of wedges (%) in class	
	c. 1980	c. 2010
Flat	74.2	68.1
High-centered	10.5	16.6
Low-centered	15.3	15.3

[1]c. 1980: color-infrared AHAP photographs,1977-1985;
c. 2010: high-resolution 35 mm photographs, 2008-2010



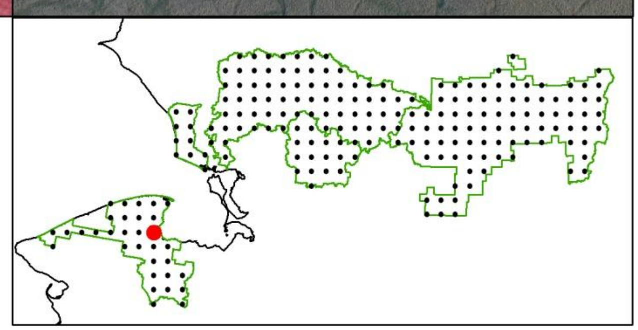


Figure 15. Ice wedge polygon morphology change. In 1978 (AHAP photo, left), ice wedge polygons were high-centered on the lower left part of the plot and mostly flat elsewhere. In 2008 (small-format photo, right) troughs appeared to have became deeper and more distinct in the region where the flat polygons were before, though different photo resolutions make the amount of change uncertain. Plot BELA_-45_183.

As a result of changes noted on the two plots between c. 1980 and c. 2010, there was a minor shift in the proportion of flat and high-centered polygons (Table 13). One of the plots with ice wedges was within a wildfire perimeter (BELA_-41_177, burned in 1977), but no change in ice wedges was noted there.

Ecological Type Changes

The cross-tabulation of ecological types (ecotypes) as recorded on c. 1980 AHAP versus c. 2010 small-format aerial photographs provides a picture of the change in area of ecotypes during this period (Table 14). For example, of 265 hexagons in ecotype "Lowland Birch Ericaceous willow Low Shrub" in c. 1980, 174 hexagons were unchanged in 2008-10, 85 hexagons in 7 plots had become "Lowland Black Spruce Forest", and a few other hexagons made less common changes (Table 14). When interpreting this table, keep in mind that the hexagons do not portray 7622 independent samples, but rather 206 plots with 37 closely spaced (i.e. spatially autocorrelated) samples (Fig. 3).

The vast majority of hexagons (94%) had no transition recorded between the two dates. Relatively few transition types accounted for most of the transitions. The 85 hexagons of "Lowland Birch Ericaceous willow Low Shrub" that became "Lowland Black Spruce Forest" mentioned above was the largest. This transition occurred by post-fire succession. About a third of the hexagons in "Lowland black spruce forest" in c. 2010 had developed by succession since c. 1980. Post-fire succession (from shrub types or birch forest to upland white spruce or mixed spruce-birch forest) is also responsible for the cluster of transitions in the far lower right-hand part of the table (n = 46 in all).

The second most important transition was the 60 hexagons of "Upland Birch Ericaceous Willow Low Shrub" (out of the original 1227 hexagons in this type) on 11 plots that changed to "Upland Alder Willow Tall Shrub". This was the most common transition produced by tundra shrub increase. Sixty-eight of the 490 hexagons in "Upland alder willow tall shrub" (14%) on the c. 2010 photos were new since c. 1980. Other less common shrub-increase transitions were "Upland sedge-dryas meadow" to "Upland alder-willow tall shrub" and to "Upland ericaceous willow low shrub" (4 and 12 hexagons, respectively).

Riverine environments were active due to fluvial processes and succession, resulting in transitions between "River barrens" and "Riverine water" (n = 29) due to channel migration, "Riverine Willow Low Shrub" to "Riverine Alder Willow Tall Shrub" (n = 8) due to succession, (perhaps enhanced by climate change), and "Riverine Willow Low Shrub" to "Riverine Barrens" (n = 6) by erosion.

Lake and pond margins, with their associated water level fluctuations and thermokarst, were responsible for a few transitions, most notably the 10 hexagons on two plots that went from "Lowland lake" to "Lowland sedge fen" (by minor lake level drop).

Thermokarst of "Black spruce forest" to "Lowland ericaceous shrub bog" produced just 4 transitions, all on one plot. The 11 hexagons of "Alpine Acidic Barrens" that transitioned to "Upland Willow Low Shrub" (and the two more that went to "Upland birch ericaceous willow low shrub") were not originally true alpine barrens but rather a low-altitude thermokarst-related thaw slump that revegetated (Fig. 11).

Table 14. Cross-tabulation of ecotypes on AHAP photography (c. 1980) and ecotypes on high-resolution photography (c. 2010)[1]

1980 Ecotype[2] \ 2010 Ecotype[2]	AlpAcidBar	AlpAlkBar	AlpDryasDwShr	AlpEricDwShr	AlpLake	AlpMafBar	AlpWetSedgMdw	CoastBar	CoastCrowberDwShr	LowAldTallShr	LowBirEricWillLowShr	LowBlackSprFor	LowEricShrBog	LowLake	LowSedgDryasMdw	LowSedgFen	LowWillLowShr
AlpAcidBar	841 (45)																
AlpAlkBar		222 (11)															
AlpDryasDwShr			921 (75)														
AlpEricDwShr				439 (45)													
AlpLake					26 (1)												
AlpMafBar						82 (4)											
AlpWetSedgMdw							24 (6)										
CoastBar								1 (1)									
CoastCrowberDwShr									19 (1)								
LowAldTallShr										7 (2)							
LowBirEricWillLowShr											174 (19)	85 (7)					
LowBlackSprFor												174 (12)	4 (1)				
LowEricShrBog													70 (7)				
LowLake											1 (1)			103 (7)		10 (2)	
LowSedgDryasMdw															18 (2)		
LowSedgFen														2 (1)		275 (22)	
LowWillLowShr																	48 (9)
RivAldWillTallShr																	
RivBar																	
RivBirWillLowShr																	
RivDryasDwShr																	
RivPopFor																	
RivWater																	
RivWetSedgMdw																	
RivWhSprWillFor																	
RivWillLowShr																	
UpAldWillTallShr																	
UpBirEricWillLowShr																	
UpBirFor																	
UpDwBirTussShr														4 (1)			
UplMafBar																	
UpSedgDryasMdw																	
UpSprBirFor																	
UpWhSprFor																	
UpWhSprLichWoodl																	
UpWillLowShr																	
Total	841 (46)	222 (12)	921 (77)	439 (45)	26 (1)	82 (4)	24 (6)	1 (1)	19 (1)	7 (2)	175 (19)	259 (13)	74 (8)	109 (7)	18 (2)	285 (23)	48 (9)

[1]Cell values are counts of hexagons representing each transition, with the count of plots in parentheses. There are 37 hexagons per plot and 206 plots; see Fig. 3. Gray shading highlights changes discussed in the text.

Table 14 (continued)[1]

1980 Ecotype[2] \ 2010 Ecotype[2]	RivAldWillTallShr	RivBar	RivBirWillLowShr	RivDryasDwShr	RivPopFor	RivWater	RivWetSedgMdw	RivWhSprWillFor	RivWillLowShr	UpAldWillTallShr	UpBirEricWillLowShr	UpBirFor	UpDwBirTussShr	UplMafBar	UpSedgDryasMdw	UpSprBirFor	UpWhSprFor	UpWhSprLichWoodl	UpWillLowShr	Total
AlpAcidBar											2 (1)								11 (1)	854 (46)
AlpAlkBar																				222 (11)
AlpDryasDwShr																				921 (75)
AlpEricDwShr																				439 (45)
AlpLake																				26 (1)
AlpMafBar																				82 (4)
AlpWetSedgMdw																				24 (6)
CoastBar																				1 (1)
CoastCrowberDwShr																				19 (1)
LowAldTallShr																	4 (1)			11 (3)
LowBirEricWillLowShr			1 (1)							3 (1)							1 (1)	1 (1)		265 (25)
LowBlackSprFor																				178 (12)
LowEricShrBog																				70 (7)
LowLake							3 (1)													117 (9)
LowSedgDryasMdw																				18 (2)
LowSedgFen																				277 (22)
LowWillLowShr																				48 (9)
RivAldWillTallShr	16 (4)																			16 (4)
RivBar		45 (9)		1 (1)		3 (1)	1 (1)		3 (2)											53 (9)
RivBirWillLowShr			24 (5)																	24 (5)
RivDryasDwShr		1 (1)		22 (5)					2 (2)											25 (6)
RivPopFor					0 (0)	1 (1)														1 (1)
RivWater	1 (1)	29 (2)				20 (8)	1 (1)		2 (1)											53 (8)
RivWetSedgMdw			2 (1)				45 (5)													47 (5)
RivWhSprWillFor								11 (3)												11 (3)
RivWillLowShr	8 (2)	6 (1)				4 (1)			79 (11)											97 (12)
UpAldWillTallShr										422 (36)							11 (2)			433 (36)
UpBirEricWillLowShr										60 (11)	1138 (77)					2 (1)	7 (3)	20 (1)		1227 (80)
UpBirFor												1 (1)				6 (1)				7 (1)
UpDwBirTussShr										1 (1)	2 (1)		1154 (55)							1161 (55)
UplMafBar														1 (1)						1 (1)
UpSedgDryasMdw										4 (3)	12 (2)				383 (30)		4 (1)			403 (30)
UpSprBirFor							1 (1)									23 (4)				24 (4)
UpWhSprFor																	365 (15)			365 (15)
UpWhSprLichWoodl																		13 (1)		13 (1)
UpWillLowShr																	1 (1)		88 (11)	89 (11)
Total	25 (5)	81 (10)	27 (5)	23 (5)	(0)	28 (8)	51 (5)	11 (3)	86 (12)	490 (41)	1154 (78)	1 (1)	1154 (55)	1 (1)	383 (30)	31 (5)	393 (17)	34 (1)	99 (11)	7622 (206)

[2]Ecotype abbreviations are explained in Table 15

Table 15. Ecotype names[1] for the abbreviations used in Table 14.

Ecotype Abbreviation	Ecotype Full Name
AlpAcidBar	Alpine Acidic Barrens
AlpAlkBar	Alpine Alkaline Barrens
AlpDryasDwShr	Alpine Dryas Dwarf Shrub
AlpEricDwShr	Alpine Ericaceous Dwarf Shrub
AlpLake	Alpine Lake
AlpMafBar	Alpine Mafic Barrens
AlpWetSedgMdw	Alpine Wet Sedge Meadow
CoastBar	Coastal Barrens
CoastCrowberDwShr	Coastal Crowberry Dwarf Shrub
LowAldTallShr	Lowland Alder Tall Shrub
LowBirEricWillLowShr	Lowland Birch-Ericaceous-Willow Low Shrub
LowBlackSprFor	Lowland Black Spruce Forest
LowEricShrBog	Lowland Ericaceous Shrub Bog
LowLake	Lowland Lake
LowSedgDryasMdw	Lowland Sedge-Dryas Meadow
LowSedgFen	Lowland Sedge Fen
LowWillLowShr	Lowland Willow Low Shrub
RivAldWillTallShr	Riverine Alder or Willow Tall Shrub
RivBar	Riverine Barrens
RivBirWillLowShr	Riverine Birch-Willow Low Shrub
RivDryasDwShr	Riverine Dryas Dwarf Shrub
RivPopFor	Riverine Poplar Forest
RivWater	Riverine Water
RivWetSedgMdw	Riverine Wet Sedge Meadow
RivWhSprWillFor	Riverine White Spruce-Willow Forest
RivWillLowShr	Riverine Willow Low Shrub
UpAldWillTallShr	Upland Alder-Willow Tall Shrub
UpBirEricWillLowShr	Upland Birch-Ericaceous-Willow Low Shrub
UpBirFor	Upland Birch Forest
UpDwBirTussShr	Upland Dwarf Birch-Tussock Shrub
UplMafBar	Upland Mafic Barrens
UpSandBar	Upland Sandy Barrens
UpSedgDryasMdw	Upland Sedge-Dryas Meadow
UpSprBirFor	Upland Spruce-Birch Forest
UpWhSprFor	Upland White Spruce Forest
UpWhSprLichWoodl	Upland White Spruce-Lichen Woodland
UpWillLowShr	Upland Willow Low Shrub

[1]Full descriptions of the ecotypes are given in Jorgenson et al. (2009)

Conclusions

Systematic sampling in this study caused us to direct our attention equally to all of ARCN, rather than to focus on areas with dramatic changes. As a result, the majority of sample plots (76%) showed no change over the approximately 30-year study interval. A sampling design that focused on change-prone areas would yield more dramatic results, but our systematic sampling design was useful in providing a balanced view of ecosystem change. In addition, it yielded baseline data to detect changes that might appear unexpectedly in places not recognized previously as "change hotspots". In view of the minor changes noted here over 30 years, the re-sampling interval for this study could be lengthened from our original proposal of 10 years to 15 or 20 years.

This study employed two different and complimentary change detection approaches: 1) a visual comparison of the 4-ha plot on two photo dates and classification of the types of changes present; and 2) identification of the ecological types on the two dates in a grid of small subplots across the 4-ha plot. The former method is faster and the results more reliable (because it is relatively easy to determine if change has or has not occurred), but it does not yield an estimate of the area which has undergone any particular change. The former method also provides a good format for recording and organizing the causal mechanisms behind the landscape changes. The latter method (ecotype classification) provides a valuable quantitative estimate of the area affected by transitions in vegetation, but classification of ecotypes is often uncertain and takes approximately 2 to 5 times as long to accomplish as simply classifying the change type on the plot as a whole.

Our systematic sample of 206 plots provided a good picture of major vegetation structural changes – changes in tree and shrub cover. An increase in shrub cover was observed on 23 plots; on the majority of these (15 plots), shrub cover increased on undisturbed tundra. An estimated 14% of the upland alder-willow tall shrub vegetation present in ARCN in 2010 had formed since 1980. Shrub increases on tundra were noted at plots scattered across all of ARCN in locations with relatively warm summers (estimated July mean temperatures 11° to 14°C). Shrub increase due to succession on floodplains (5 plots) was the other major mode of shrub increase, though this count of transitions was not statistically significantly different from the count of plots on floodplains where shrubs decreased due to river erosion (n = 1).

Increases in tree cover were observed on 15 of the 206 plots; the majority of these (10 plots) were in forested areas that were undergoing post-fire succession from shrub to lowland black spruce. About a third of the lowland black spruce forest area in 2010 had formed from shrub vegetation since 1980. No forested plots burned by wildfire during the study time interval, in spite of more frequent fires in Alaska during the study period than previous decades (Kasischke 2010). On 4 plots trees increased by white spruce colonization of upland tundra; all of these plots were in locations with relatively warm summers (estimated July mean temperatures 12° to 14°C).

Many other typical forms of arctic and subarctic landscape change were recorded on just one or a few plots. These included conversion of lowland black spruce forest to unforested wetland by thermokarst, expansion of water bodies by thermokarst, partial drainage of a lake by thermokarst, drying of a lake in a river terrace, erosion of vegetation communities by migration of river channels, degradation of ice wedges, and revegetation of a thaw slump.

Our sample of 206 plots spaced at 20 km intervals represents a good compromise between cost and ability to detect network-wide changes, especially for the mountains and uplands that cover most of ARCN. However, certain change phenomena cover relatively small areas (e.g., those enumerated in the previous paragraph) and are thus limited in our study design by a small sample size. This is a special concern for the lowland areas of ARCN, which cover about one quarter of the area and are represented by about 50 plots. The lowlands have numerous lakes and abundant ice-rich sediments that are highly susceptible to thermokarst; we consider lakes and permafrost to be of particular interest from a climate-change perspective. Thus ARCN is pursuing additional monitoring strategies for surface water area (as a part of the Terrestrial Landscape Patterns and Dynamics Vital Sign) and permafrost (as a part of the Permafrost Vital Sign; for details, see http://science.nature.nps.gov/im/units/arcn/).

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